Development and Implementation of Virtual Field Teaching Resources: Two Karst Geomorphology Modules and Three Virtual Capstone Pathways

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Abstract. During the summer of 2020, many geology field camps were cancelled due to the COVID-19 pandemic, including the Karst Geomorphology field course I was scheduled to co-teach through Western Kentucky University. When the National Association of Geoscience Teachers (NAGT) in collaboration with the International Association for Geoscience Diversity (IAGD) began the project of supporting working groups to create online field experience teaching materials, this presented an opportunity. This manuscript describes the development of two activities derived from that field camp curriculum that are now freely available as peer-reviewed Exemplary Teaching Activities on the Science Education Resource Center (SERC) Online Field Experiences repository: "Karst Hydrogeology: A virtual field introduction using © Google Earth and Geographic Information Systems (GIS)" and "Karst Hydrogeology and Geomorphology: A virtual field experience using © Google Earth, GIS, and TAK [Topographic Analysis Kit]." Each product includes a student handout, an instructor workflow reference, a grading rubric, and NAGT-established learning objectives. The introductory activity is the more basic of the two, is expected to take about one 8-hour day to teach, and walks students through all the steps, as well as providing global examples of karst landscapes to virtually explore. The other activity, Karst Hydrogeology and Geomorphology, assumes student familiarity with © Google Earth, GIS, and karst drainage systems, and is expected to take about twice as long as the introductory activity to teach. To make these learning opportunities financially accessible, all software required for the activities is open-source, and alternative workflows for the introductory module are provided so that the entire exercise can be completed using a mobile device. Addressing this need for virtual capstone options during the pandemic and providing a virtual alternative for years to come, these karst activities, along with a subset of other SERC activities were assembled into three learning tracks, each one providing learning hours equivalent to a traditional field camp, that have been added to the course offerings at the University of Cincinnati Department of Geology. In addition to providing online capstone activities in the time of a pandemic, these learning materials provide alternative experiences to traditional field camps that are inclusive for all geoscience students.

1 Introduction

This manuscript presents in detail the development of two virtual field experiences: "Karst Hydrology: A Virtual Field Introduction Using © Google Earth and Geographic Information Systems (GIS)," and "Karst Hydrogeology and Geomorphology: A virtual field experience using © Google Earth, GIS, and Topographic Analysis Kit (TAK)." Following the

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description of these specific activities, three Virtual Capstone Pathways are presented that incorporate the karst modules in addition to several other activities from the Science Education Resource Center (SERC) Online Field Experiences repository (https://serc.carleton.edu/NAGTWorkshops/online_field/activities.html). Finally, the content of an interview with the instructor of those pathways is presented as a preliminary evaluation of the materials following their initial offering by the Department of Geology at the University of Cincinnati.

Both karst activities described in this paper are available in the SERC repository as part of the **Teaching with Online Field Experiences Exemplary Collection**. This exemplary rating is an official designation resulting from the peer review process (Burmeister et al., 2020) for the Teach the Earth portal for Earth Education.

These activities were designed with a constructivist teaching approach (Brooks and Brooks, 1999). Structure is provided to guide students as they explore questions pertaining to karst landscapes. After completion of the activities, they may have developed a deeper understanding of the complexities of karst hydrology and geomorphology, and an accelerated curiosity to learn more. In each activity, students are guided through the technical details of using opensource software tools to select and explore a karst landscape. Detailed step-by-step instructions are provided for obtaining digital elevation models (DEMs) from Internet sources, and then visualizing and analyzing these landscapes with QGIS, an opensource GIS software. Instruction on performing more advanced landscape analysis is provided in the advanced module when students use TAK to perform flow routing over their DEM.

While both activities require Internet access for participation, socio-economic and accessibility barriers were considered in an attempt to provide opportunities for more inclusive learning experiences. Therefore, all parts of both activities were built around using opensource software. Additionally, if a learner does not have a laptop or other personal computer in their home, an alternative workflow for the introductory activity is presented, such that the entire activity can be completed using a smartphone or Internet-enabled tablet. This approach, considering universal design for learning (UDL), provides students with multiple means of representation for an accessible learning experience. Additionally, the learning assessment for these activities is written such that there is flexibility in the way individual students or small groups of students present their findings so that multiple means of expression are built in. These activities are designed for 100% online delivery, either synchronously, asynchronously, or using a combination of those approaches. Addressing physical and nonphysical barriers, incorporating UDL, and teaching field experiences synchronously online, have been proven to provide more inclusive learning experiences (Carabajal and Atchison, 2020).

Prior to the COVID-19 pandemic, many virtual field experiences were premised on some people being able to access the field while others were not able. Technology, such as two-way video conferencing in a remote collaboration model was used to include everyone in the field experience (Carabajal et al., 2017; Marshall, 2018). However, in some cases, entire classes were not able to access the field due to logistical or institutional situations. Instructors in these cases pioneered taking advantage of technology such as drones, LiDAR, structure-from-motion photogrammetry, and © Google Earth to bring the field to the classroom (Atchison and Feig, 2011; Clary and Wandersee, 2010; Dolphin et al., 2019; Granshaw, 2011). It is to these latter

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cases we looked when refining the choices of technology and software when, in 2020, no one could access those in-person field experiences.

1.1 Learning Objectives

The group guiding the NAGT/IAGD joint effort to develop remote learning experiences for the 2020 field camp season collaborated to determine a set of learning objectives (NAGT, 2020). All activities developed as a part of this initiative were expected to address as many of these as possible (Table 1).

Table 1. NAGT Virtual Field Experiences learning objectives and how they were applied to the karst activities.

NAGT Learning Objective	Corresponding Goal for Karst Activities
1. Design a field strategy to collect or select data in order to answer a geologic question.	1. Choose a karst field area. Find and retrieve appropriate topographic data from Internet sources.
2. Collect accurate and sufficient data on field relationships and record these using disciplinary conventions (field notes, map symbols, etc.).	2. Read additional information about karst area and take notes. Import topographic data to QGIS and reproject to correct coordinate reference system (CRS).
3. Synthesize geologic data and integrate with core concepts and skills into a cohesive spatial and temporal scientific interpretation.	3. Generate hillshade and topographic contour layers for landscape using QGIS. Identify karst landform features.
4. Interpret earth systems and past/current/future processes using multiple lines of spatially distributed evidence.	4. Use QGIS landscape visualization to develop interpretation of water flow routes.
5. Develop an argument that is consistent with available evidence and uncertainty.	5. In advanced activity, compare and contrast manual versus automated flow routing. Develop hypotheses and experiment designs that could be used for further study
6. Communicate clearly using written, verbal, and/or visual media (e.g., maps, cross-sections, reports) with discipline-specific terminology appropriate to your audience.	6. Create effective visualizations, present results to cohort if working with one, and submit a written report with figures to the instructor.
7. Work effectively independently and collaboratively (e.g., commitment, reliability, leadership, open for advice, channels of communication, supportive, inclusive).	7. Both activities require independent work, and if there is the opportunity, group work is encouraged.
8. Reflect on personal strengths and challenges (e.g., in study design, safety, time management, independent and collaborative work).	8. A reflection component is included as part of the written report.

9. Demonstrate behaviors expected of professional geoscientists (e.g., time management, work preparation, collegiality, health and safety, ethics).   9. Professional behavior is expected of all participants.

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2 Karst Hydrology: A Virtual Field Introduction Using © Google Earth and GIS

Through the activity, Karst Hydrology: A Virtual Field Introduction Using © Google Earth and GIS,
75 https://serc.carleton.edu/NAGTWorkshops/online_field/activities/237039.html, students have the opportunity to select and virtually explore the hydrogeology and geomorphology of a karst landscape using © Google Earth, LiDAR-data-sourced digital elevation models (DEM), geologic maps, and GIS software (QGIS) such that they gain an understanding of karst landscapes and their associated hazards, access to and analysis of Internet-based remote sensing data, and verbal and written communication of scientific information. This basic activity is suitable for use in upper-level undergraduate geomorphology
80 or groundwater hydrogeology courses, or as part of a capstone activity for graduating seniors. The main concepts explored are karst geomorphology, karst hydrogeology, © Google Earth image interpretation, and basic GIS landscape analysis, including coordinate reference system reprojection, hillshade raster generation, and elevation contour extraction.

Karst landscapes refer to regions where the predominant groundwater storage and flow is through discrete conduits or cave passages. Surface streams tend to be scarce and short in length when they do occur. Landforms typical of karst include caves,
85 sinkholes, dolines, poljes, fensters, sinking streams, springs, and vertical shafts (Fig. 1). According to Goldscheider et al. (2020), "15.2% of the global ice-free continental surface is characterized by the presence of karstifiable carbonate rock." Because of this relative prevalence of karst and its particular environmental vulnerability, it is important that students receive significant academic exposure to the way water behaves in karst aquifers.

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>
> **Commented [RB8]:** updated citation
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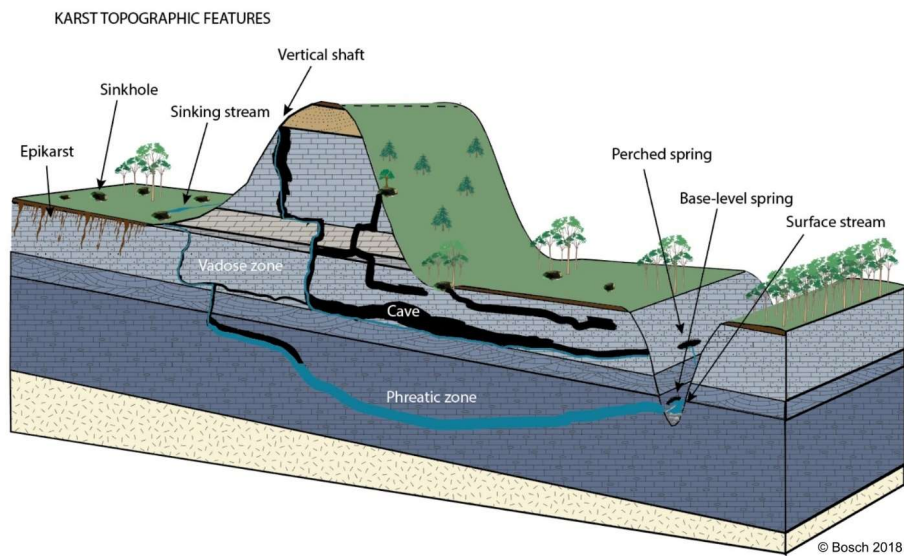
> **Commented [RB9]:** Defined karst landscape

90 **Figure 1. Block diagram of generalized karst topography. Drawing by author.**

2.1 Expectations

While there is no specific prerequisite coursework, students are expected to have familiarity with the concept of karst landscapes and topographic map reading. Additionally, previous experience with © Google Earth and other geographical information systems is helpful, but not necessary. This introductory activity is expected to take from four to eight hours to

95 complete and can be taught as a stand-alone exercise or in conjunction with other modules to build a capstone field experience.

2.2 Learning Goals

The learning goals for this introductory karst activity are consistent with the NAGT/IAGD effort objectives outlined in the Introduction (Table 1):

- Content/conceptual goals for this activity

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  - Visually identify karst landscapes (particularly in contrast to fluvial landscapes) from aerial imagery.
  - Interpret topographic maps to determine drainage patterns.

- Higher order thinking goals for this activity
    - Compare and contrast the water drainage patterns of a karst watershed with a surface stream network or porous-media groundwater aquifer.
    - Integrate digital and analog data.
    - Analyze digital and analog data to draw conclusions about landscape-associated hazards.
- Other goals for this activity
    - Navigate © Google Earth.
    - Search the Internet, including USGS's Earth Explorer website.
    - Manipulate data in a GIS for analysis and presentation.
    - Oral presentation or video presentation
    - Teamwork synchronously and asynchronously
    - Technical writing
    - Reflection
    - Self-assessment
    - Data management
    - Independence
    - Personal management
    - Time management
    - Leadership

2.3 Activity description and teaching materials

About 16.5 percent of the world's population either lives on, or obtains their water from, karst landscapes (Goldscheider et al., 2020). It is therefore important that we understand the drainage patterns, potential hazards to humans, and potential threats to water quality that are unique to karst landscapes. In this exercise, students select and virtually explore a karst landscape. Materials available on the SERC repository include a student handout, teaching notes, a grading rubric, and several Internet links for background and supplemental information. The teaching notes include a step-by-step walkthrough of the activity procedure, including screenshots of the anticipated outcomes. This way the modules can be available to a wide range of instructors and learners.

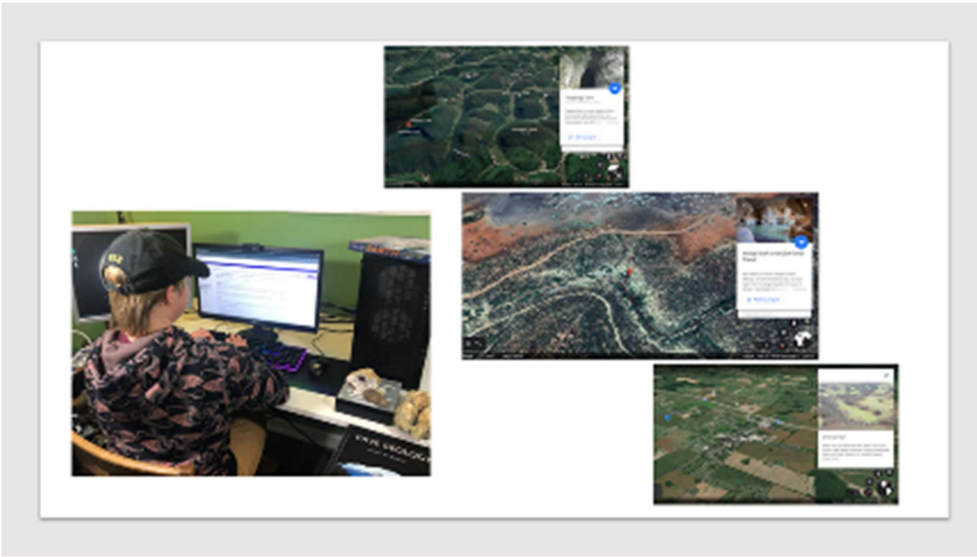
For this activity, students need access to an Internet enabled laptop or other device; © Google Earth on web, mobile, or desktop; and a geographic information system (GIS). QGIS (https://www.qgis.org/en/site/) is recommended as a free and open source option which works best as a desktop download. As part of this exercise, students may have the opportunity to experience manipulating DEM data with a GIS. However, the reality is that not all students have access to a laptop, and GIS tools in mobile devices may not offer full functionality. One option for a fully mobile-based activity is to bypass the GIS steps and move straight from © Google Earth to accessing a pre-existing topographic map. Mobile apps change frequently, so there is a

135 legacy issue in promoting specific apps. However, USGS has created a great tutorial video (closed-captioning embedded in the video) for how to access topo maps from a mobile device: https://www.usgs.gov/media/videos/using-us-topo-and-historic-topo-maps-your-mobile-device. For this approach, students would skip steps 2, 3, and 4 (which are outlined below), following the procedure in the USGS video. They can then use a drawing app on their device to complete step 5.

Students may work in groups or independently to complete the activity. Presentations may be delivered as a group, and final
140 reports should be written and submitted independently.

The activity begins by providing resources for students to review the basics of karst hydrology. On the student handout, there are © Google Earth links for seven different field areas from around the world. These locations were selected to provide learners with the option to study a karst area on any continent (with the exception of Antarctica) and to present karst areas that are well-known or otherwise geologically or biologically significant. The intent is that one of these areas may pique a student's
145 interest and keep them engaged throughout the activity. Learners can browse © Google Earth and select among these options for a karst region to focus on for the remainder of the exercise (Fig.2):

Commented [RB10]: Explanation as to why these locations were selected

- Central Kentucky Karst, USA
- El Sotano de las Golondrinas, Mexico
- Caverna de Santana, Brazil
150 • Sof Omar Cave, Ethiopia
- Postojna Cave, Slovenia
- Tenglong Cave, China
- Waitomo Cave, New Zealand

155 **Figure 2. Student choosing a karst area to study. Images of the © Google Earth pages for Tenglong Cave, China, Sof Omar Cave, Ethiopia, and the Central Kentucky Sinkhole Plain, United States, as examples. Photo by author.**

1. Once students have selected their karst landscape, they need to acquire topographic and geologic map information. For locations in the United States, Earth Explorer (https://earthexplorer.usgs.gov/) is a good source for SRTM digital elevation model (DEM) files. Students who choose sites outside of the

160 United States can still find their DEM data, but will need to search the Internet to obtain it. A walk-through with screenshots of this workflow is available in the Teaching Notes.

2. The DEM file then needs to be uploaded to a GIS. For many DEMs, students will need to find the appropriate CRS and reproject their raster. References are provided for students to review the Universal Transverse Mercator System and find UTM zones, along with detailed directions for reprojecting DEMs

165 in QGIS.

3. After their project is in the correct CRS, they generate a Hillshade layer to better visualize the topography (Fig. 3). They then answer the following questions: What karst aquifer region did you select? What UTM Zone is this field site in? What color band worked best for your visualization of the topography? What does the Hillshade function do? How is it helpful?

170 4. This projected and shaded map should now render a more accurate and realistic visualization of the chosen field site. To better understand the drainage patterns of this landscape, they extract two sets of

topographic contour lines: one set for all the contour lines and a second, more widely spaced set, for index contours. They are asked what contour intervals they chose and why (Fig. 4).

5. Now that students have detailed topographic maps with contour intervals, they are given a resource to revisit the rule of V's for determining flow paths over land surfaces (Olivas, 2017). If students have access to a printer, they can print out a paper copy of the map they built and draw the drainage patterns in with a pencil. There are two digital options for drawing in the water flow paths. For the first, students can export the image of their map in QGIS as png format and then use a photo editor to draw flow paths on their maps. There are many software packages available to complete this step. A couple of opensource options are © Google slides (Fig. 5) and Inkscape. Students may also choose to work directly in the GIS and create a new vector layer to manage their surface flow paths. Here are the questions posed to students after this step: Describe the flow paths you drew on your map. What challenges or obstacles did you encounter while determining the routes water would take? What environmental or natural-disaster hazards do you think might be issues in this landscape?

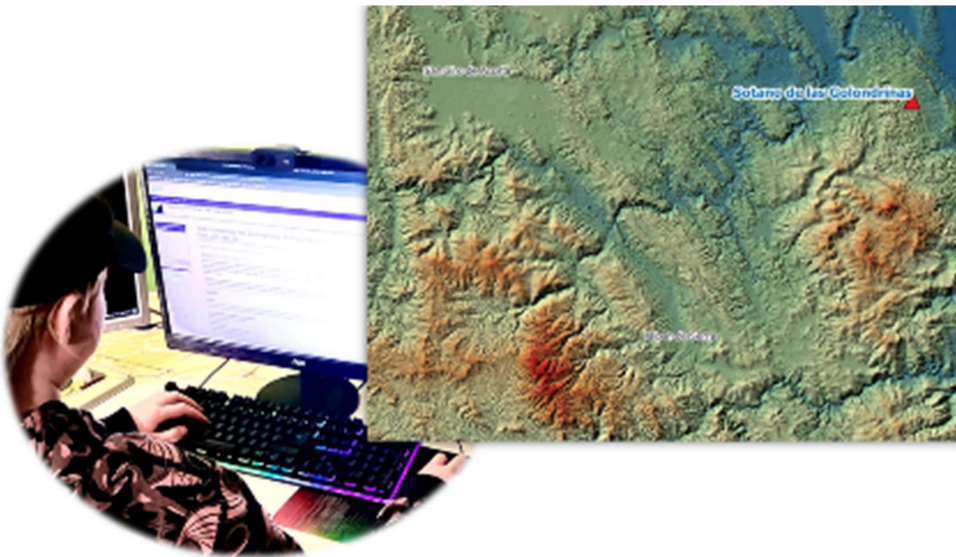



Figure 3. Reprojected, hillshaded, and colored-by-elevation digital elevation model of the Sotano del las Golondrinas area, Mexico, in QGIS. Photo by author.

Figure 4. El Sotano de las Golondrinas area with elevation contour layers. Photo by author.

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OR

Figure 5. Manually drawn water flow paths created in © Google Slides (left) and iPhone photo markup (right). Photo by author.

2.4 Assessment

Questions for students are provided in the student handout (Appendix A). These are to guide students' thinking as they work
through the activity. They can then use their responses to the questions as they prepare their presentations and write their final
reports.

After completing the exercise as individuals or in small groups, students share their findings with the whole class. This can
happen virtually or in person as circumstances dictate. Each presentation can happen as a slideshow or as a video made by the
student(s), or in any way that works for instructor(s) and student(s).

Each student also writes a formally structured report (Title, author's name, date, abstract, introduction, methods, results,
discussion, conclusion). Within the report or as a separate document, they should reflect on their experience with this activity
and assess their level of understanding before and after the activity of a.) © Google Earth, b.) GIS, c.) UTM CRS, d.)
topographic map interpretation, and e.) karst hydrogeology. A rubric to guide the grading of these materials is provided with
the   activity   on   the   SERC   repository
(https://d32ogoqmya1dw8.cloudfront.net/files/teachearth/activities/grading_rubric_karst_intro_activity.docx).

2.5 Recommendation to instructors

It is possible that students may be unfamiliar with using a GIS before attempting to work through this activity. In the event
that there is difficulty following the directions in the student handout, there is also a photographic walkthrough provided for
instructors:
https://d32ogoqmya1dw8.cloudfront.net/files/NAGTWorkshops/online_field/activities/intro_karst_hydrogeology_teaching_
notes.docx. This document should be useful if learners or instructor have difficulty with GIS. The example in the walkthrough
uses the karst landscape provided for the Central Kentucky Karst, USA. If students are struggling to understand and complete
the activity, working with the example from Kentucky may make it easier to provide them with more structured guidance.
There may be other students who need additional challenge. These learners can be prompted to access the advanced module
(described below) to continue with more involved analysis of their karst landscape.

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3 Karst Hydrogeology and Geomorphology: A virtual field experience using © Google Earth, GIS, and TAK

While completing Karst Hydrology and Geomorphology: A virtual field experience using © Google Earth, GIS, and TAK,
https://serc.carleton.edu/NAGTWorkshops/online_field/activities/237267.html, students have the opportunity to select and
virtually explore the hydrogeology and geomorphology of a karst landscape using © Google Earth, LiDAR-data-sourced
DEM(s), geologic maps, GIS software, and topographic analysis software packages such that they gain an understanding of
karst landscapes and their associated hazard risks, access to and analysis of Internet-based remote sensing data, design of field
strategy, and verbal and written communication of scientific information. This activity incorporates and builds upon the
material covered in Karst Hydrogeology: A virtual field introduction using © Google Earth and GIS. This advanced activity,

like the companion introductory activity, is suitable for use in upper-level undergraduate or graduate geomorphology or groundwater hydrogeology courses, or as part of a capstone activity for graduating seniors. The main concepts explored are karst geomorphology, karst hydrogeology, © Google Earth image interpretation, GIS landscape analysis, hypothesis development, and field strategy planning.

3.1 Expectations

This advanced module assumes that students have prior experience with the use of © Google Earth and other geographic information systems, as well as familiarity with the concepts of karst landscapes, topographic map reading, and geologic map reading. This can be taught as a stand-alone exercise or in conjunction with other modules to build a capstone field experience and is expected to take eight to sixteen hours to complete.

3.2 Learning Goals

The learning goals for the advanced virtual karst activity are also consistent with the NAGT virtual field learning objectives presented above (Table 1):

- Content/conceptual goals for this activity
  - Visual identification of karst landscapes (particularly in contrast to fluvial landscapes) from aerial imagery.
  - Analog vs. digital topographic map interpretation to determine drainage patterns.
  - Effective field strategy planning to address an original hypothesis.
- Higher order thinking goals for this activity
  - Compare and contrast the ways karst drainage basins behave differently than purely surface stream or porous-media groundwater.
  - Analyze digital and analog data to draw conclusions about landscape-associated hazards.
  - Compare and contrast analog with digitally automated analyses.
  - Formulate hypotheses using analog and digital data.
  - Develop an experimental strategy to test these hypotheses.
- Other skills goals for this activity
  - Georeferencing analog data to a GIS
  - Geologic history construction
  - Navigating © Google Earth
  - Searching the Internet and/or USGS's EarthExplorer website
  - Manipulating data in a GIS for analysis and presentation
  - Oral presentation or video presentation
  - Teamwork synchronously and asynchronously
  - Technical writing

- o Reflection
- o Self-assessment
- o Data management
- o Independence
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- o Personal management
- o Time management
- o Leadership

3.3 Activity description and teaching materials

This advanced activity is similar to the introductory activity in that students select and virtually explore a karst landscape.
265 Materials available on the SERC repository include a student handout, teaching notes, a grading rubric, and several Internet links for background and supplemental information. The teaching notes include a step-by-step walkthrough of the activity procedure, including screenshots of the anticipated outcomes. This way the modules can be available to a wide range of teachers and learners.

For this activity, students need access to an Internet enabled laptop. Prior to the activity, they will need to download and install
270 the following software packages: © Google Earth on web or desktop, a GIS (QGIS is a free and open source option), and Topographic Analysis Kit (TAK) (free, open source software package available at Github, https://github.com/amforte/Topographic-Analysis-Kit). Students may work in groups or independently to complete the activity and presentation. Final reports should be written and submitted independently.

This activity begins with students exploring the World Karst Aquifer Map (Goldscheider, 2021; Fig. 6) and its associated
275 article by Goldscheider et al. (2020). Instead of being provided with seven choices as in the introductory activity, they are presented with the opportunity to use these resources along with © Google Earth to select any karst area to study. Instructors may want to place a time limit on this first portion of the activity.
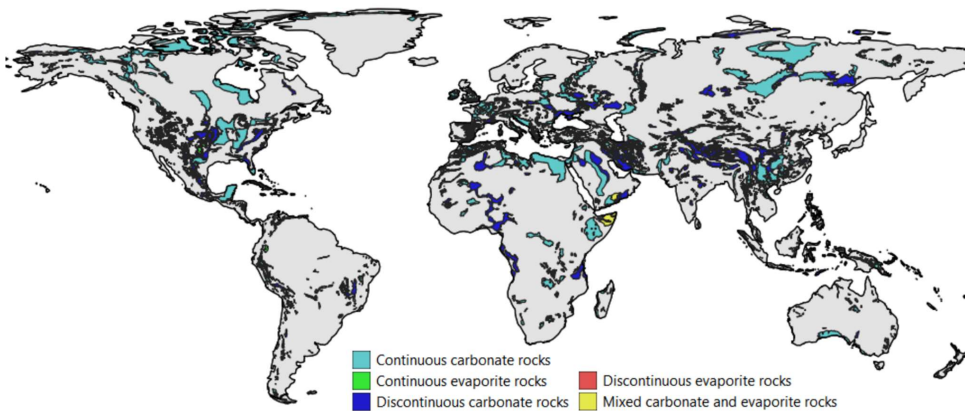
Figure 6. World Karst Aquifer Map (cartography by author in QGIS, data from Goldscheider, 2021).

280   1.   Once students have selected their karst landscape, they need to acquire topographic and geologic map information. For locations in the United States, Earth Explorer is a good source for DEM files. Students who choose sites outside of the United States can still find their DEM data, but will need to do some Internet searching to obtain them. A walk-through with screenshots of this workflow is available in the Teaching Notes. They will then follow the instructions for the introductory activity described above, following steps 2 through 5.

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    2.   To determine flow paths more objectively, students use TAK. This software uses a set of Matlab functions written by Adam Forte which build upon the functionality of TopoToolbox by Wolfgang Schwanghart and Dirk Scherler. Students then load the Reprojected DEM into TAK and run "MakeStreams" to perform automated flow routing. This is the only function used in the activity, but hopes are that some students' interest will be piqued to explore further landscape analysis.

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    3.   Students then add the streams vector layer generated by TAK to their GIS project.

    4.   The final piece of data students add to their GIS is regional geology. The student handout provides instruction for importing a shapefile or for manually georeferencing an analog geologic map.

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    5.   They are then ready to begin the analysis portion of the activity. This analysis will be presented to the class if they are working in a cohort and the responses to the following steps will be written into their final report.

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6. There will be differences between the manual flow routing drawn by students and the flow paths modeled by the routing algorithms in TAK (Fig. 7). They are called upon to speculate about the source of those differences, and then to consider the strengths and weaknesses of each approach. They then decide which method they think provides better results. This conclusion may vary based upon the student or the selection of field study location. When assessing student performance of this step, it is more important that the student has constructed a reasonable argument based upon the evidence than that they have chosen the flow routing method that the instructor thinks is right.

7. Using observations of the geology, the topography, and the hydrology, students construct a geologic/geomorphic history of their study area (Fig. 8). They are asked to determine the sequence of events at this site, and to consider in particular, depositional, tectonic, and erosional events. They are also asked how any stream network (or lack thereof) evolved.

8. Now that they have constructed a story, they are reminded that they have done this with limited evidence. They are asked think about their level of confidence for each event and state which events they think may need more support. They build those into hypotheses.

9. Additional hypotheses may be developed concerning environmental or natural hazards they think might be issues with this landscape.

10. The final step is to describe a potential experiment that would test one or more of the hypotheses proposed in 8 and 9. The students first state what data they would need to collect to support or refute their hypotheses and speculate as to the kinds of results that may be obtained for different types of data as well as what implications these results might have for each hypothesis. Finally, they are asked what field, laboratory, or numerical techniques would be required to obtain these data, and to be specific as if they were planning for field work, lab work, or numerical modeling.

Compare manual and automatic flow routing results

Figure 7. Manually drawn water flow routing (left) and automated flow routing performed in TAK (right).

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Figure 8. Advanced activity synthesis, clockwise from left: analog geological map draped over topography using QGIS, DEM with hillshade in QGIS, manually drawn flow routing, and elevation contour layers in QGIS. Photo by author.

3.4 Assessment

Questions for students are provided in the student handout (Appendix B). These are to guide students' thinking as they work
330 through the activity. They can then use their responses to the questions as they prepare their presentations and write their final reports.

After completing the exercise as individuals or as small groups, students share their findings with the whole class. This can happen virtually or in person as circumstances dictate. Each presentation can happen as a slideshow or as a video made by the student(s), or in any way that works for both instructor(s) and student(s).

335 Each student writes a formally structured report (title, author's name, date, abstract, introduction, methods, results, discussion, conclusion). Within the report or as a separate document, they should reflect on their experience with this activity and assess their level of understanding before and after the activity of a.) © Google Earth, b.) GIS, c.) UTM CRS, d.) topographic map interpretation, e.) TAK, e.) karst hydrogeology, f.) geologic history construction, g.) hypothesis formulation, and h.) scientific experiment design.

340 A rubric to guide the grading of these materials is provided with the activity on SERC (https://d32ogoqmya1dw8.cloudfront.net/files/NAGTWorkshops/online_field/activities/grading_rubric_karst_hydrogeology _geomorphology_virtual_field_experience_us.docx).

3.5 Recommendation to instructors

Some students may need more supervision and guidance when selecting a karst area to focus on. It is suggested that these
345 students choose a study area that is in their home country. This may make it easier for them to locate the DEM files and manipulate the data to complete the activity. If students need additional direction, they may refer to the introductory activity to use of the of the karst landscapes suggested there.

There may be other students who want to extend their learning. There are a few ways people can find addition challenge within the scope of this activity. One way to do this is to explore some of the other landscape analysis options available in QGIS or
350 TAK and then integrate those results into the proposed chronology for the area. Another option would be to choose a second karst landscape or a non-karst landscape, complete the same steps as with the first landscape, and compare the results from those two exercises. A third possible extension would be to explore other flow routing algorithms. A few different flow routers can be found in the Toolbox under the Processing menu in QGIS. For students familiar with Linux who want to try another opensource topographic analysis software, they can install LSDTopoTools
355 (https://lsdtopotools.github.io/LSDTT_documentation/index.html) and then compare flow routing results from that tool with those obtained manually and with TAK. Another possible exercise for students who need an additional challenge is that they

may try to find a karst landscape using © Google Earth to search the surface of Mars or the Moon, and compare that with the karst landscape they have investigated on Earth's surface.

4 Virtual Capstone Pathway Design

360   Existing modules, including the aforementioned karst activities, developed in the early months of the COVID-19 pandemic, from the SERC Teaching with Online Experiences page, were sorted into three interest-based tracks: Planetary Geology, Traditional Geology, and Environmental Geology (Tables 2, 3, and 4, respectively). Since these activities include information on SERC about how long they should take to complete, each path was able to be tailored such that they have an estimated instructional equivalent to 28 days in the field—approximating a four- to six-week field camp—and they would thus each be

365   suitable for a senior capstone experience. In addition to providing a safer route for students to meet their graduation criteria during a pandemic, these Virtual Capstone Pathways are a robust and rigorous alternative for students who are not able to attend a traditional field camp.

Table 2. Modules for a Planetary Geology Virtual Capstone Pathway

Track:	Planetary Geology	
Module Name	Field day equivalent	URL
Uncertainty Modules	0.5	https://serc.carleton.edu/NAGTWorkshops/online_field/activities/237278.html
JMARS training	0.5	https://serc.carleton.edu/teachearth/activities/236955.html
Fold Analysis Challenge	1	https://serc.carleton.edu/geode/activities/217440.html
Using StraboSpot for Field Sedimentology & Stratigraphy	1	https://serc.carleton.edu/NAGTWorkshops/online_field/activities/237339.html
Introduction to Planetary Mapping	1	https://serc.carleton.edu/teachearth/activities/236956.html
Geologic Mapping of a Virtual Landscape	2	https://serc.carleton.edu/NAGTWorkshops/online_field/activities/236670.html

Orienteering in Minecraft	1	https://serc.carleton.edu/NAGTWorkshops/online_field/activities/237088.html
Karst Hydrogeology: A virtual field introduction using © Google Earth and GIS	1	https://serc.carleton.edu/NAGTWorkshops/online_field/activities/237039.html
Volcano mapping on Mount Cleveland volcano	5	http://master32.cas.usf.edu/fieldschool/bearing/bearing3.html http://master32.cas.usf.edu/fieldschool/UTM/utm1.html http://master32.cas.usf.edu/fieldschool/volume/volume.html http://master32.cas.usf.edu/fieldschool/cleveland-map/cleveland-map.html http://master32.cas.usf.edu/fieldschool/isomass/isomass.html
Virtual Geologic Mapping Exercise at Lough Fee, Ireland	3	http://csmgeo.csm.jmu.edu/Geollab/Whitmeyer/geode/Lough_Fee/ https://serc.carleton.edu/NAGTWorkshops/online_field/activities/237160.html
Geologic Mapping of a Virtual Landscape II – Three River Hills	3	https://serc.carleton.edu/NAGTWorkshops/online_field/activities/237061.html
Geologic mapping on Mars	4	https://serc.carleton.edu/NAGTWorkshops/online_field/activities/237044.html
A virtual fieldtrip on the coastal geomorphology of Naxos Isl.	5	https://serc.carleton.edu/NAGTWorkshops/online_field/activities/238032.html
	28	

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Table 3. Modules for Traditional Geology Virtual Capstone Pathway

Module Name	Field day equivalent	URL
Uncertainty Modules	0.5	https://serc.carleton.edu/NAGTWorkshops/online_field/activities/237278.html
Fold Analysis Challenge	1	https://serc.carleton.edu/geode/activities/217440.html
Using StraboSpot for Field Sedimentology & Stratigraphy	1	https://serc.carleton.edu/NAGTWorkshops/online_field/activities/237339.html
Reconnaissance stratigraphy and mapping of the Frying Pan Gulch, MT	5	https://serc.carleton.edu/NAGTWorkshops/online_field/activities/237089.html
Karst Hydrogeology: A virtual field introduction using © Google Earth and GIS	1	https://serc.carleton.edu/NAGTWorkshops/online_field/activities/237039.html
Volcano mapping on Mount Cleveland volcano	5	http://master32.cas.usf.edu/fieldschool/bearing/bearing3.html http://master32.cas.usf.edu/fieldschool/UTM/utm1.html http://master32.cas.usf.edu/fieldschool/volume/volume.html http://master32.cas.usf.edu/fieldschool/cleveland-map/cleveland-map.html http://master32.cas.usf.edu/fieldschool/isomass/isomass.html
Virtual Geologic Mapping Exercise at Lough Fee, Ireland	3	http://csmgeo.csm.jmu.edu/Geollab/Whitmeyer/geode/Lough_Fee/ https://serc.carleton.edu/NAGTWorkshops/online_field/activities/237160.html
Sage Hen flat	6	https://serc.carleton.edu/NAGTWorkshops/online_field/activities/238026.html

Module Name	Field day equivalent	URL
Remote Mapping and Analytical data integration: Coal Creek quartzite and Ralston shear zone, Colorado	5	https://serc.carleton.edu/NAGTWorkshops/online_field/activities/237694.html
	27.5	

Table 4. Modules for Environmental Geology Virtual Capstone Pathway

Module Name	Field day equivalent	URL
Uncertainty Modules	0.5	https://serc.carleton.edu/NAGTWorkshops/online_field/activities/237278.html
Fold Analysis Challenge	1	https://serc.carleton.edu/geode/activities/217440.html
Using StraboSpot for Field Sedimentology & Stratigraphy	1	https://serc.carleton.edu/NAGTWorkshops/online_field/activities/237339.html
Quaternary mapping in Bells Canyon as an introduction to ArcGIS Pro	1	https://serc.carleton.edu/NAGTWorkshops/online_field/activities/237280.html
Go with the Flow: A Virtual Field Experience on Groundwater Flow	3	https://serc.carleton.edu/NAGTWorkshops/online_field/activities/237415.html
Volcano mapping on Mount Cleveland volcano	5	http://master32.cas.usf.edu/fieldschool/bearing/bearing3.html http://master32.cas.usf.edu/fieldschool/UTM/utm1.html http://master32.cas.usf.edu/fieldschool/volume/volume.html http://master32.cas.usf.edu/fieldschool/cleveland-map/cleveland-map.html http://master32.cas.usf.edu/fieldschool/isomass/isomass.html

Virtual Geologic Mapping Exercise at Lough Fee, Ireland	3	http://csmgeo.csm.jmu.edu/Geollab/Whitmeyer/geode/Lough_Fee/ https://serc.carleton.edu/NAGTWorkshops/online_field/activities/237160.html
Birth of a River in Yellowstone National Park	2	https://serc.carleton.edu/NAGTWorkshops/online_field/activities/237410.html
Landslide Mapping and Analysis Module	5	https://serc.carleton.edu/NAGTWorkshops/online_field/activities/237687.html
Karst Hydrogeology and Geomorphology: A virtual field experience using © Google Earth, GIS, and TAK	2	https://serc.carleton.edu/NAGTWorkshops/online_field/activities/237267.html
A virtual fieldtrip on the coastal geomorphology of Naxos Isl.	5	https://serc.carleton.edu/NAGTWorkshops/online_field/activities/238032.html
	28.5	

375

5 Karst Activities and Virtual Capstone Pathways Implementation

The Department of Geology at the University of Cincinnati first offered the Virtual Capstone Pathways during the Spring 2021 semester with instructor Dr. Dan Sturmer. Two students enrolled under the course catalog listing of "Geology Capstone, 100% Online". As only two students have attempted this course so far, we do not yet have enough data for a rigorous review of the
380 success of this program. Here are comments from Dr. Sturmer (2021) on the implementation of these Virtual Capstone Pathways:

> For . . . the course, we have been following the general [Traditional Geology] track. We had plans to run concurrent tracks this summer, but I am not sure that we will have enough students to do that. Overall, I think both students have really enjoyed the program. We meet via Zoom once a week to go over that week's assignment and we sometimes
385 meet additional times during the week. I have mostly broken down the assignments so that 2 days of work is completed in a week (for example they are doing the 6-day Sage Hen Flat assignment over 3 weeks).
>
> It has been a little challenging doing this over a semester instead of over a concentrated time because the students have other classes and obligations, so the experience is different. I think they have learned a lot of valuable skills and one of the benefits is they get to work on projects all over the world and from a wider variety of branches of the
390 geosciences than they would in person.

Dr. Sturmer reported that the students "said they really liked the order of the assignments because they were able to build upon skills that they learned in previous assignments." His feedback on the karst activities was this: "For the Karst assignment, the students generally didn't have too much trouble with it. They were mostly not familiar with QGIS (which I found surprising!) but they were able to complete the assignment with guided instruction." Furthermore, Dr. Sturmer stated that these Virtual
395 Capstone Pathways are an "important option to have," and that the Department will be keeping this as a Capstone opportunity to provide to students in the future, alongside the options of attending an in-person field camp or completing an original research project. Benefits he cited to this choice of capstone are that it costs the students less, it can be managed to accommodate students' time constraints, and it provides an accessible option.

Commented [RB16]: These materials were recently developed in response to the pandemic, which is in keeping with the theme of this special issue. They have only been deployed once, and for that one implementation, there was a cohort of two students. I interviewed the instructor who taught this, and his comments have been included in the manuscript. This manuscript primarily documents this moment in time of the pandemic, the response to it, the development of these learning tools, and to the extent possible, the implementation of those tools.

6 Discussion

400 Embedded within the challenges presented by the COVID-19 pandemic, there were opportunities. Our communities have grown stronger and developed new strategies because we were forced to think, learn, and work in new ways during 2020. These two karst activities, "Karst Hydrology: A Virtual Field Introduction Using © Google Earth and GIS," and "Karst Hydrogeology and Geomorphology: A virtual field experience using © Google Earth, GIS, and TAK," are just a couple of the products that emerged out of necessity when we were finding new ways to teach the field because we couldn't get groups of
405 people to the field. These products were well received, but they were not the only exemplary modules to emerge from the pandemic in 2020; there are 71 teaching activities listed in the SERC Online Field Experiences repository. Aligning this great supply of quality teaching activities with a demand for online capstone learning opportunities produced the Virtual Capstone

Pathways: Planetary Geology, Traditional Geology, and Environmental Geology. These have been successful so far at the University of Cincinnati and provide good option so that all students can get learning opportunities that fit with their needs.

Commented [RB17]: Expanded discussion

410 Recently, remote learning and online conferences have provided a chance to develop new tools that will make for more equitable academic experiences in the years ahead. In addition to keeping everyone safe during the pandemic, the geoscience community used this time to perform some large-scale, collective introspection. New tools and ways of working, including the virtual field experiences and virtual capstone pathways described in this manuscript, are an instrumental part of our community working to become for welcoming, accessible, and inclusive.

415 **Acknowledgments**

This work was made possible by Chris Atchison, Kurt Burmeister, Anne Egger, Katherine Ryker, and Basil Tikoff, who coordinated the geoscience community to join together during the pandemic of 2020 to provide a large set of freely available virtual field learning experience activities. Aida Farough and Bridget Mulvey, as co-leaders for the Hydrogeology/Environmental Geology working group provided invaluable support as I, and other members of the team,
420 designed our activities. Much gratitude is due to Lisa Shantz for reaching out via email to ask about capstone opportunities during the pandemic. Lisa played a key role in motivating me to develop the Virtual Capstone Pathways! Thank you to Craig Dietsch and Krista Smilek in the UC Department of Geology for embracing my Virtual Capstone Pathways design and to Dan Sturmer for work hard implementing it. Aaron Bird did wonderfully as cinematographer for the activity promotion video that I presented at GSA 2020 Connects Online. I am grateful to Ian Castro, Brooke Crowley, and Chris Atchison for reviewing this
425 manuscript prior to submission. Finally, thanks go out to Samuel Bosch-Bird for modeling as the "student" in all photos.

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490 Tenglong Cave, China

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Appendix A. Introductory Activity: Student Handout

Karst Hydrogeology: A virtual field introduction using © Google Earth and GIS

- By Rachel Bosch, University of Cincinnati   karstgeomorph@gmail.com

A.1 Summary

505 Students will have the opportunity to select and virtually explore the hydrogeology and geomorphology of a karst landscape using © Google Earth, LiDAR data-sourced DEM(s), and GIS software (QGIS) such that they gain an understanding of karst landscapes and their associated hazards, access to and analysis of Internet-based remote sensing data, and verbal and written communication of scientific information.

A.2 Activity Description

510 Karst aquifers supply drinking water to 25% of our world's population. It is therefore important that we understand the drainage patterns, potential hazards to humans, and potential threats to water quality that are unique to karst.

Prior to beginning this activity, download and install the following software packages: © Google Earth on web or desktop (https://www.google.com/earth/versions/) and a GIS (QGIS is a free and open source option: https://www.qgis.org/en/site/).

1. Background. Review background information on karst and on the source of the digital elevation model (DEM) data
515   used in this activity.

Background information on karst: https://link.springer.com/article/10.1007/s10040-016-1519-3, https://kgs.uky.edu/kgsweb/olops/pub/kgs/ic04_12.pdf, https://en.wikipedia.org/wiki/Karst, http://www.igme.es/boletin/2016/127_1/BG_127-1_Art-9.pdf.

Background on specific karst areas you can explore during this activity:

520 - Central Kentucky Karst, USA   https://www.usgs.gov/science-support/osqi/yes/national-parks/mammoth-cave-national-park,

http://www.igme.es/boletin/2016/127_1/BG_127-1_Art-9.pdf

- El Sotano de las Golondrinas, Mexico https://en.wikipedia.org/wiki/Cave_of_Swallows
- Caverna de Santana, Brazil https://en.wikipedia.org/wiki/Caverna_Santana

525 - Sof Omar Cave, Ethiopia

https://en.wikipedia.org/wiki/Sof_Omar_Caves

- Postojna Cave, Slovenia

https://www.postojnska-jama.eu/en/, https://www.slovenia.info/en/stories/karst, https://izrk.zrc-sazu.si/en/predstavitev#v

- Tenglong Cave, China

530 https://en.wikipedia.org/wiki/Tenglong_Cave

- Waitomo Cave, New Zealand

https://www.newzealand.com/us/waitomo-caves/, https://en.wikipedia.org/wiki/Waitomo_Glowworm_Caves

Background on the Shuttle Radar Topography Mission (SRTM) to acquire the data used in the DEMs recommended in this activity: https://www2.jpl.nasa.gov/srtm/

535 For an overview of karst aquifers on Earth, refer to the World Karst Aquifer Map (WOKAM), available at https://www.whymap.org/whymap/EN/Maps_Data/Wokam/wokam_node_en.html. Use WOKAM to select an area of interest, browse © Google Earth to search for karst landforms, or use one of the following links to go directly to a karst area:

- Central Kentucky Karst, USA https://earth.google.com/web/search/smiths+Grove,+KY,+USA/@37.050087,-86.20808355,191.9936422a,4259.47719636d,35y,0h,0t,0r/data=CigiJgokCUJ0d1jEiEJAEea5ieZmhUJAGblW8S1
540 QglXAIfK61_HlhlXA
- El Sotano de las Golondrinas, Mexico https://earth.google.com/web/search/S%c3%b3tano+De+Las+Golondrinas,+Guadalupe,+Tamapatz,+San+Luis+Pot osi,+Mexico/@21.5998365,-99.0989649,851.98715572a,974.07941593d,35y,0h,45t,0r/data=CrUBGooBEoMBCiUweDg1ZDY4NzUzMGM5O
545 DE4Y2I6MHhiMTBkYjMzYzJlMmI4ZmY2GXVyhuKOmTVAIew84HBVxljAKkhTw7N0YW5vIERlIExhcyBH b2xvbmRyaW5hcywgR3VhZGFsdXBlLCBUYW1hcGF0eiwgU2FuIEx1aXMgUG90b3NpLCBNZXhpY28YAiA BIiYKJAlg4DFGCoxCQBGnW-OjiYFCQBnCoi9tkINVwCGM0IDIN4dVwCgC
- Caverna de Santana, Brazil https://earth.google.com/web/search/Caverna+de+Santana+-+SP-165,+Iporanga+-+State+of+S%c3%a3o+Paulo,+Brazil/@-24.5350913,-
550 48.7020552,293.73887977a,950.74006882d,35y,0h,45t,0r/data=Cq8BGoQBEn4KJTB4OTRjNGEwMTVjN2I5Y2 ZmNzoweGEzYTRhODFjOGFmMGFkMjkZxt9RvvuIOMAhTf7d8dxZSMAqQ0NhdmVybmEgZGUgU2FudGFu YSAtIFNQLTE2NSwgSXBvcmFuZZ2EgLSBTdGF0ZSBvZiBTw6NvIFBhdWxvLCBCcmF6aWwYAiABIiYKJAn -rpcTGk9BwBFs-6kNOVpBwBmno36HsCJMwCGxtmypGkBMwCgC
- Sof Omar Cave, Ethiopia
555 https://earth.google.com/web/search/Holqa+Soof+Umar(Sof+Omar+Cave),+Ethiopia/@6.9066847,40.8452162,122 2.69076013a,1047.96286517d,35y,0h,45t,0r/data=CpMBGmkSYwolMHgxN2M5NjQ3OWExYmYwYTlmOjB4M 2M0OWM0MGQ0NTY4NmM3MhlgIjn0caAbQCFShmALMGxEQCooSG9scWEgU29vZiBVbWFyKFNvZiBPb WFyIENhdmUpLCBFdGhpb3BpYRgCIAEiJgokCSUX6kNEvCXAEeDqGh5t1CXAGVLTbZJyqkJAIaUkWEZBn
UJAKAI
560 - Postojna Cave, Slovenia
https://earth.google.com/web/search/Postojna+Cave,+Jamska+cesta,+Postojna,+Slovenia/@45.7830298,14.203841 7,554.79907402a,710.07777756d,35y,0h,45t,0r/data=CpoBGnASagolMHg0NzdiMzFlMWNkNzA4YjJiOjB4OGQ 0NzIwZmZmYjJkMDJiZRmPZQtSOuRGQCFBH3bwXWgsQCovUG9zdG9qbmEgQ2F2ZSwgSmFtc2thIGNlc3R

565   hLCBQb3N0b2puYSwgU2xvdmVuaWEYAiABIiYKJAmdY770WsYbQBGh1tN8XZkbQBk6SL5K8XBEQCFCd
RMcK2tEQCgC

- Tenglong   Cave,   China
https://earth.google.com/web/search/tenglong+cave/@30.331922,108.983322,1420.20643916a,896.95198141d,35y,
0h,45t,0r/data=CngaThJICiUweDM2OGZkMDk3MjVlN2I4Yzc6MHg2ZDE0NDE1Y2I1ZTlhMTU2GarSFtf4VD5
AIf3bZb_uPltAKg10ZW5nbG9uZyBjYXZlGAIgASImCiQJ0VlSXZlXPkARWxZ1aX9LPkAZ1uuihSQ_W0AhBZ
570   y09hI8W0AoAg
- Waitomo   Cave,   New   Zealand   https://earth.google.com/web/search/waitomo+cave/@-
38.23941234,175.06756931,225.98846243a,29217.75304527d,35y,0h,0t,0r/data=CnYaTBJGCiQweDZkNmNiN2I
yMTU0MjlhMDM6MHg1MDBlZjYxNDNhMzE2YjAZCTTY1HkhQ8AhWE18WqrjZUAqDHdhaXRvbW8gY2F
2ZRgCIAEiJgokCYgiAEfsmEHAEbC50VaO-EPAGbZq90dRGWVAIeafOmPIUGbA

575

2. Data acquisition. Acquire topographic information for your chosen karst landscape. For locations in the United States, Earth Explorer is a good source for **SRTM DEM files** (https://earthexplorer.usgs.gov/). For sites outside of the US you can still find DEM data, but may need to do additional Internet searching to obtain it.

3. Data processing.

580   a. The DEM file then needs to be uploaded to a **GIS**. Check the properties of your DEM raster layer to see what CRS it loaded in. For many DEMs, you will need to find the appropriate CRS and **reproject** the raster. For a review of the Universal Transverse Mercator (UTM) System, here is a link to the USGS fact sheet (https://pubs.usgs.gov/fs/2001/0077/report.pdf) and a world map of UTM zones (https://maptools.com/tutorials/grid_zone_details). Another option is to use an interactive online map

585   (https://mangomap.com/robertyoung/maps/69585/what-utm-zone-am-i-in-) to help determine the coordinate system for your location. The reproject task is performed by selecting the layer for the DEM raster data. Then click on the "raster" drop down menu. Go to "projections," and select "Warp (reproject)..." Then select a complete path for output and give a name to the output file for the reprojected map data.

b. After the project is in the correct CRS, you can then choose a color scheme (right click on the layer >

590   "properties" > "style" > "render type" > "singleband pseudocolor" > "generate a new color map" > select the desired color band > "classify") and make a **Hillshade** layer to better visualize the topography. To generate a Hillshade layer, again use the "raster" menu. Go to "Terrain analysis" > "Hillshade…"

    i. *Questions: What karst aquifer region did you select? What UTM Zone is this field site in? What colorband worked best for your visualization of the topography? What does the Hillshade function*

595   *do? How is it helpful?*

c. To better understand the drainage patterns of this landscape, extract a set of topographic contour lines. A the "raster" menu. Go to "Extraction" > "Contour…" A good interval to start with a 20. If the contour lines end up looking too crowded or too spread out, you can make new contour layers with different intervals.

d. Now that you have detailed topographic maps with contour intervals, you may want to revisit the rule of V's for determining flow paths over land surfaces (http://uncivilengineer.net/2017/07/14/watercourses-and-ridges-on-topographic-maps-why-the-vs/).

If you have access to a printer, you can print out a paper copy of the map you built and draw the drainage patterns in with a pencil. There are two digital options for drawing in the water flow paths. For the first, you can export the image of their map in QGIS as png format. To do this go to the "Project" menu and select "Save as Image…" Then use a photo editor to draw flow paths on the map. If you have more GIS experience you may want to work directly in the GIS and make new vector layers to create surface flow paths.

i. *Questions: Describe the flow paths you drew on your map. What challenges or obstacles did you encounter while determining the routes water would take?*

Sharing science:

1. After completing the exercise, as an individual or as part of a small group, present your findings to the whole class.

2. Write a formally structured report (Title, author's name, date, abstract, introduction, methods, results, discussion, conclusion). Within the report or as a separate document, reflect on your experience with this activity and assess your level of understanding before and after the activity of a.) © Google Earth, b.) GIS, c.) UTM CRS, d.) topographic map interpretation, and e.) karst hydrogeology.

Appendix B. Advanced Activity: Student Handout

Karst Hydrogeology and Geomorphology: A virtual field experience using © Google Earth, GIS, and TAK

o **By Rachel Bosch, University of Cincinnati   karstgeomorph@gmail.com**

B.1 Summary

Students will have the opportunity to select and virtually explore the hydrogeology and geomorphology of a karst landscape using © Google Earth (or perhaps © Google Mars or © Google Moon if they so choose), LiDAR data-sourced DEM(s), geologic maps, GIS software, and topographic analysis software packages such that they gain an understanding of karst landscapes and their associated hazard risks, access to and analysis of Internet-based remote sensing data, design of field strategy, and verbal and written communication of scientific information.

This activity incorporates and builds upon *Karst Hydrogeology: A virtual field introduction using © Google Earth and GIS.* If you have already completed the introductory activity, use your results from that activity and continue onto this activity with step 3.f.

B.2 Activity Description

Karst aquifers supply drinking water to 25% of our world's population. It is therefore important that we understand the drainage patterns, potential hazards to humans, and potential threats to water quality that are unique to karst.

630 Prior to beginning this activity, download and install the following software packages: © Google Earth on web or desktop (https://www.google.com/earth/versions/); a GIS (QGIS is a free and open source option: https://www.qgis.org/en/site/); Topographic Analysis Kit (free, open source software package available at Github: https://github.com/amforte/Topographic-Analysis-Kit)

1. Background. Review background information on karst and on the source of the digital elevation model (DEM) data
635 used in this activity.

Background information on karst: https://link.springer.com/article/10.1007/s10040-016-1519-3,

https://kgs.uky.edu/kgsweb/olops/pub/kgs/ic04_12.pdf, https://en.wikipedia.org/wiki/Karst,

http://www.igme.es/boletin/2016/127_1/BG_127-1_Art-9.pdf.

Background on the Shuttle Radar Topography Mission (SRTM) to acquire the data used in the DEMs recommended in this
640 activity: https://www2.jpl.nasa.gov/srtm/

2. Data acquisition.

a. For an overview of karst aquifers on Earth, refer to the **World Karst Aquifer Map (WOKAM)**, available at https://www.whymap.org/whymap/EN/Maps_Data/Wokam/wokam_node_en.html. Use WOKAM to select an area of interest or browse © Google Earth to search for karst landforms.

645 b. As a base layer for GIS mapping of your karst area, load the WOKAM **shapefiles** to view the chosen area in the context of its broader karst region. WOKAM shapefiles can be found at https://produktcenter.bgr.de/terraCatalog/OpenSearch.do?search=473d851c-4694-4050-a37f-ee421170eca8&type=/Query/OpenSearch.do or in the attached zipped folder.

c. Acquire topographic and geologic map information for your chosen karst landscape. For topography in the
650 United States, Earth Explorer is a good source for **SRTM DEM files** (https://earthexplorer.usgs.gov/). For sites outside of the US you can still find DEM data, but may need to do additional Internet searching to obtain it.

d. Acquire geologic map data. Inside of the US, the **National Geologic Map Database** project should have what you need (https://ngmdb.usgs.gov/ngmdb/ngmdb_home.html). Outside of the US, it will vary country
655 by country and more Internet searching will be needed. Geologic information may be in a file format ready for import to a GIS or as a scanned image or pdf file.

3. Data processing.

a. The DEM file then needs to be uploaded to a **GIS**. Check the properties of your DEM raster layer to see what coordinate reference system (CRS) it loaded in. For many DEMs, you will need to find the appropriate

660 CRS and **reproject** the raster. For a review of the Universal Transverse Mercator (UTM) System, here is a link to the USGS fact sheet (https://pubs.usgs.gov/fs/2001/0077/report.pdf) and a world map of UTM zones (https://maptools.com/tutorials/grid_zone_details). Another option is to use an interactive online map (https://mangomap.com/robertyoung/maps/69585/what-utm-zone-am-i-in-) to help determine the coordinate system for your location. The reproject task is performed by selecting the layer for the DEM

665 raster data. Then click on the "raster" drop down menu. Go to "projections," and select "Warp (reproject)..." Then select a complete path for output and give a name to the output file for the reprojected map data.

    b. After the project is in the correct CRS, you can then choose a color scheme (right click on the layer > "properties" > "style" > "render type" > "singleband pseudocolor" > "generate a new color map" > select the desired color band > "classify") and make a **Hillshade** layer to better visualize the topography. To

670 generate a Hillshade layer, again use the "raster" menu. Go to "Terrain analysis" > "Hillshade…"

        i. *Questions: What karst aquifer region did you select? What UTM Zone is this field site in? What colorband worked best for your visualization of the topography? What does the Hillshade function do? How is it helpful?*

    c. The next layer to upload to GIS is geologic map information.

675   i. If the geologic map data is in a proper file format for GIS, it will most likely need to be reprojected to the same CRS as the elevation data (see step 3a).

        ii. If the geologic map data is a scanned image, you have two options:

            1. Import the image to the GIS and georeference it to align it with the map. The procedure for georeferencing analog images is covered in this webinar

680   (https://www.youtube.com/watch?v=WbMdNvQcCOs); or

            2. Work side-by-side comparing the information from your geologic map with that on the GIS. This is less precise, but if you are careful you can make it work.

    d. To better understand the drainage patterns of this landscape, extract a set of topographic contour lines. Again, use the "raster" menu. Go to "Extraction" > "Contour…" A good interval to start with a 20. If the contour

685 lines end up looking too crowded or too spread out, you can make new contour layers with different intervals.

    e. Now that you have detailed topographic maps with contour intervals, you may want to revisit the rule of V's for determining flow paths over land surfaces (http://uncivilengineer.net/2017/07/14/watercourses-and-ridges-on-topographic-maps-why-the-vs/).

If you have access to a printer, you can print out a paper copy of the map you built and draw the drainage patterns in with a

690 pencil. There are two digital options for drawing in the water flow paths. For the first, you can export the image of their map in QGIS as png format. To do this go to the "Project" menu and select "Save as Image…" Then use a photo editor to draw flow paths on the map. If you have more GIS experience you may want to work directly in the GIS and make new vector layers to create surface flow paths.

i. *Questions: Describe the flow paths you drew on your map. What was your reasoning for electing to draw the flow paths you did? What challenges or obstacles did you encounter while determining the routes water would take? How did you overcome the challenges/obstacles to determine the routes?*

f. To determine flow paths more objectively, use a software designed with flow-routing algorithms. Here we will use Topographic Analysis Kit (TAK). You first need to give the software the output files name prefix and select the output directory. Then load the Reprojected DEM (GeoTIFF file) into TAK. If it gives you an error regarding whole numbers, don't worry, your file has still loaded correctly. Check the box labeled "Resample" and then click "Run MakeStreams." This is as far as this activity goes as far with using TAK, but it is a powerful tool for doing geomorphological analysis. If you are curious, I recommend you check out the documentation at Github and explore it further on your own.

g. From the TAK output file folder, drag and drop your new shapefile into the GIS. If you do not see your streams overlaying the topography, right click on your streams vector layer name. Go to "Properties" > "General" > "Coordinate Reference System." Select the appropriate CRS. Click on "Update extents", "Apply", "OK."

4. Data analysis.

a. Compare the stream network predicted by TAK with the one you drew in step 11. *What similarities or differences do you see between the two networks? Which one do you think is more accurate? Why?*

b. Using your observations of the geology, the topography, and the hydrology, construct a geologic/geomorphic history of your study area. *What was the sequence of events at this site—consider in particular depositional, tectonic, and erosional events? How did the stream network (or lack thereof) evolve?*

5. Hypothesis formulation.

a. Some events in your above history will be more hypothetical than others. Please state which events need additional testing to be able to defend them.

b. What environmental or natural-disaster hazards do you think might be issues in this landscape? Why do you think this? Write these ideas in the form of additional hypotheses about this landscape.

6. Experimental design.

a. What data would you need to collect to support or refute your hypotheses? Please speculate as to the kinds of results that may be obtained for different types of data and what implications those might have for each hypothesis.

b. What field, laboratory, or numerical techniques would be required to obtain the data you need? Please be specific as if you were planning for field work, lab work, or numerical modeling.

Sharing science:

1. After completing the exercise, as an individual or as part of a small group, present your findings to the whole class.

2. Write a formally structured report (Title, author's name, date, abstract, introduction, methods, results, discussion, conclusion). Within the report or as a separate document, reflect on your experience with this activity and assess your level of understanding before and after the activity of a.) © Google Earth, b.) GIS, c.) UTM CRS, d.) topographic map interpretation, e.) TAK, e.) karst hydrogeology, f.) geologic history construction, g.) hypothesis formulation, and h.) scientific experiment design.

 Appendix C. List of Internet Resources

URL with full citation	Description
Bosch, Rachel, "From Field to Phone: A Karst Camp Chronicle," (2020), https://www.youtube.com/watch?v=3YvbUOlBRs0.	Video presentation of the materials in this manuscript
Bosch, Rachel, "Karst Hydrogeology and Geomorphology: A virtual field experience using Google Earth, GIS, and TAK," *Teaching with Online Field Experiences Exemplary Teaching Activity Collection* and *On the Cutting Edge Exemplary Collection,* May 2020, https://serc.carleton.edu/NAGTWorkshops/online_field/activities/237267.html	Advanced karst activity
Bosch, Rachel, "Karst Hydrogeology: A virtual field introduction using Google Earth and GIS," *Teaching with Online Field Experiences Exemplary Teaching Activity Collection* and *On the Cutting Edge Exemplary Collection,* May 2020, https://serc.carleton.edu/NAGTWorkshops/online_field/activities/237039.html	Introductory karst activity
https://earthexplorer.usgs.gov/	Earth Explorer, website for obtaining DEM files and other digital geographic data
https://github.com/amforte/Topographic-Analysis-Kit	Official website for downloading TAK
https://lsdtopotools.github.io/LSDTT_documentation/index.html	Official website for downloading LSDTopoTools
https://serc.carleton.edu/NAGTWorkshops/online_field/activities.html	Science Education Resource Center (SERC) Online Field Experiences repository
https://www.google.com/earth/	Official website for © Google Earth
https://www.qgis.org/en/site/	Official website for downloading QGIS
https://www.usgs.gov/media/videos/using-us-topo-and-historic-topo-maps-your-mobile-device	USGS tutorial on accessing topographic maps from a mobile device